Lifetime of the DØ Silicon Tracker

DØ Collaboration
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Summary

In this report we discuss the probable limits to the lifetime of the DØ Silicon Microstrip Tracker (SMT). Our estimate of the lifetime is based on the locations and types of detectors and tracking requirements for Run II (section II), our knowledge and measurements of the phenomenology of radiation damage as a function of dose (sections III, IV), and the actual dose received in the Tevatron environment (section V). We expect that the lifetime of the SMT will be limited by micro-discharge breakdown of the junction in the Micron-supplied detectors in the inner four barrels. This will begin to occur at bias values of ~150 volts and all channels will fail at bias values of ~200 volts. This means that we will start to lose significant numbers of channels at an integrated luminosity of 3.6 fb-1 and that 100% of the channels on the inner layer will be dead by 4.9 fb^{-1}. Errors in estimating the micro-discharge formation and dose accumulation lead to uncertainties in these numbers of about 50%.

I. Silicon Tracker Geometry and Detectors

The DØ Silicon Microstrip Tracker (SMT), shown in Fig. 1, is a mixture of disk and barrel modules intended to provide both central and forward tracking for collisions over the long luminous region of the Tevatron. The tracker was originally designed, and the detectors tested, for an expected lifetime of 2 fb^{-1}. In this note we discuss the damage rate and pathologies expected for extended Tevatron running, and discuss how the expected damage will affect the performance of the experiment.

The SMT uses a variety of detector geometries, technologies and types. Detectors were fabricated by three companies (Micron, Elma, and Eurisys) using three technologies (single sided (SS), double sided (DS), and double sided-double metal(DSDM)). Varieties and locations of detectors are enumerated in Table 1. Each detector technology and manufacturer has distinct characteristic behavior when irradiated.

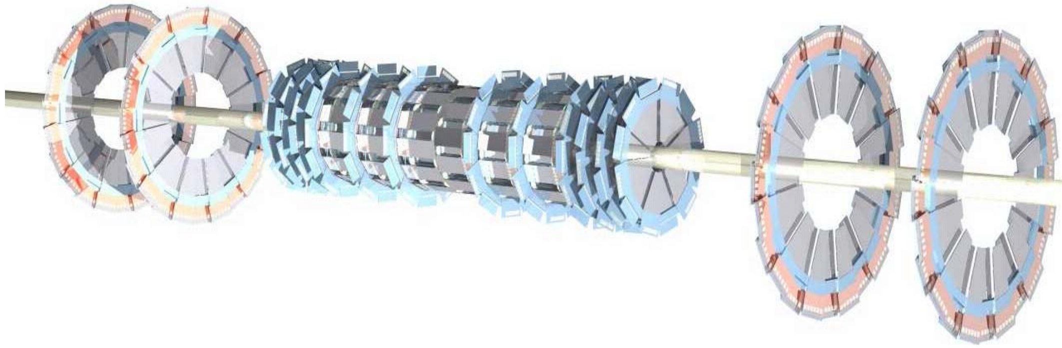

Figure 1 Three dimensional view of the SMT. The two outer barrel modules and large diameter outer disks use single sided detectors. The length of the central disk/barrel region is 1.1 meters.

Module	Type	Layer	Inner Radius (cm)	Outer Radius (cm)	Manufacturer
Central Disk	DS	-	2.57	9,96	Micron, Eurisys
Outer Disk	SS	-	9.5	26	Elma
Central Barrels	DSDM	1	2.715	3.645	Micron
	DS	2	4.55	5.554	
	DSDM	3	6.768	7.582	
	DS	4	9.101	10.51	
Outer Barrels	SS	1	2.715	3.645	Micron
	DS	2	4.55	5.554	
	SS	3	6.768	7.582	
	DS	4	9.101	10.51	

Table 1 SMT detector geometries and types DS-double sided, SS-single sided DSDM – double sided double metal.

The devices most strongly affected by radiation will be the inner barrel layer and the inner portion of the central disks. The inner layer of the barrels is crucial for B hadron identification. Loss of axial information in the inner barrel layer will degrade the impact parameter resolution in r-ϕ by ~30%. We estimate that this degraded r-ϕ resolution will cause the double b tag efficiency to drop from 45% to 32% in top quark events[1]. Loss of stereo information in the inner barrel will degrade the vertex Z resolution by a factor of 2.3 [2]. The Run2b tracker, assuming no radiation damage to the SMT, is designed to have 30% higher b-pair tagging efficiency and a mistag rate a factor of two lower than the Run2a detector [3 4].

At 396 ns bunch spacing and L = 2 x 10^{32} $cm^{-2}s^{-1}$ there will be an average of 5 interactions/crossing[5]. The Run IIa tracker is not designed for this level of occupancy and has no redundancy. Not only will track resolution suffer due to the loss of the inner layer; the tracking efficiency will fall and the number of mis-reconstructed tracks will rise due to the high occupancy in the fiber tracker. Track reconstruction time, already a significant factor in DØ, rises rapidly with the number of interactions per crossing and will become unacceptable with 5 interactions/crossing and no silicon inner layer information. The combination of the loss in resolution, along with the increasingly difficult tracking environment due to multiple interactions, will make the DØ tracker performance for Higgs physics unacceptable with the loss of the inner layer. The loss of the inner layer is therefore the benchmark for the useful lifetime of the Run IIa tracker.

II. Radiation Damage Mechanisms

There is a substantial literature on radiation damage in silicon detectors, much of the data coming from LHC, especially RD48 [6] and SSC studies [7]. This work allows us to understand the overall character of radiation damage expected in the SMT but is not sufficient to provide a precise lifetime prediction. Depletion voltage change and surface charge effects depend on silicon material and the manufacturing process and must be studied for each detector type. Leakage current effects are expected to be more uniform among technologies. The major radiation effects on silicon detectors are:

- Increase of leakage current. This effect is usually described by $I=I_0\ \alpha\ \phi$ Amp/cm^3 where I_0 is the initial detector current density, ϕ is the particle flux, and α is a time and temperature dependent parameter which is independent of silicon manufacturer or detector type[8]. Increased leakage currents will cause increased shot noise.

- Trapped and surface charges in insulating layers. Trapped charge in oxide layers is the most significant radiation effect on electronics as the resultant fields in the oxide will shift the operating point of CMOS transistors. Radiation induces positive charge centers in the silicon oxide layers which form AC coupling capacitors or separate metal layers in silicon detectors. These charges influence the fields near the surface of the detector and can reduce the breakdown potential of the strip junctions. The effect is dependent on the details of the insulating layer formation and electrode geometry and alignment and can vary significantly among manufacturers. In double sided detectors, fields at the p-n junction are increased by the field between the p implant held at the bias voltage and the aluminum AC coupling structure which is held at the SVX input voltage of ~1 volt. This additional field can lower the threshold for junction breakdown and cause “micro-discharge” [9]. This is a significant effect for our Micron detectors and is expected to limit their lifetime.

- Change in the effective impurity concentration. Non-ionizing radiation causes the removal of donor states and formation of additional acceptor impurities in the bulk silicon, causing n-type detectors to become p-type and increasing the depletion voltage. This effect is quite complex and is dependent on silicon type, manufacturer, time, and temperature. There is short term (~50h at room temperature), “beneficial” annealing as well as long term (~500 days at room temperature) “reverse” annealing. After inversion from n to p-type at about 300Krad reverse annealing will increase the depletion voltage. Annealing rates can be minimized by operating at low temperature (below 0 C). The detector temperature must be kept low for most of it’s lifetime or damage centers “frozen” at low temperature will be activated and significantly increase the depletion voltage. Slopes of the impurity concentration vs. dose curve and annealing rates have been shown to depend on manufacturer, type of radiation (neutron vs. pion) and oxygen concentration in the bulk silicon[3].

The change in effective impurity concentration will eventually lead to very high depletion voltages. Voltage applied to AC coupled detectors is limited by the micro-discharge effect and breakdown of the AC coupling capacitors. Operation at less than the nominal depletion voltage will lead to significant loss of performance. Irradiated detectors need to be over-depleted for full charge collection[10]. We expect 5-10% charge loss simply from operating at nominal depletion. Operation of the detectors under full depletion voltage will lead both to a decrease in charge collection and increase in width of the charge clusters on the r-ϕ measuring side. DØ data from booster irradiation is shown in Fig. 2. Charge deposit is simulated using an infrared laser. The increased charge cluster widths before full depletion are due to charge diffusion in the undepleted bulk silicon. The time needed to collect the charge is increased and will result in additional loss of charge in 132 ns operation. The combination of increased width and incomplete charge collection will rapidly reduce signal/noise for operation below full depletion.

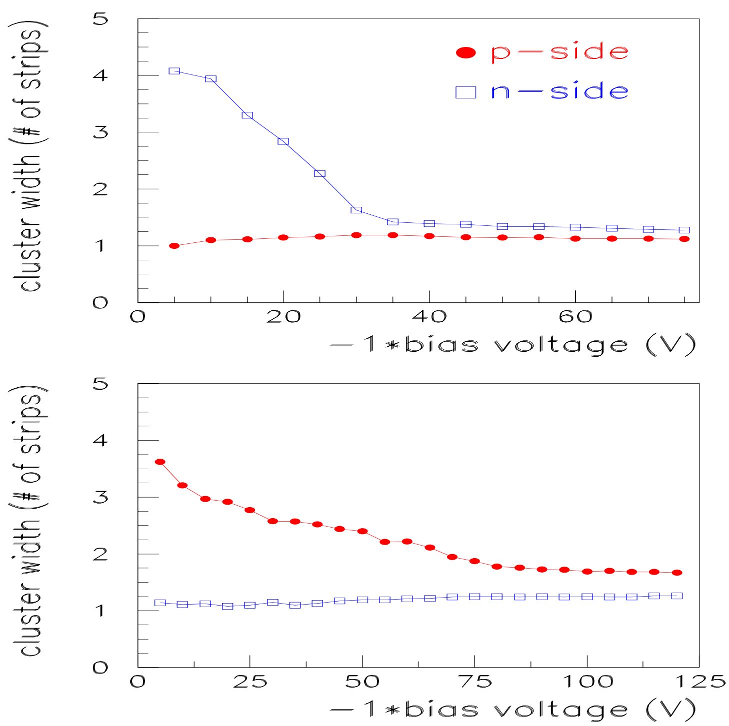

Figure 6: *The cluster width as a function of the bias voltage is shown for the p-side (filled dots) and the n-side (open squares) before (top) and after irradiation (bottom).*

10

Figure 2 Cluster size as a function of bias for unirradiated (top) and type inverted detectors (bottom).

III. Detector Damage Studies

DØ has a longstanding program of studies aimed at understanding the radiation performance of silicon detectors and the SVX chip. Studies of detectors and chips were performed at TRIUMF and the Lowell, MA neutron facility, in addition to a continuing program of studies in the Fermilab booster[11]. The most relevant studies for predicting the lifetime of the Run IIa SMT were performed with spare production detectors in the Fermilab Booster in 2000. These detectors are identical to those installed in the collision hall and include mechanical support structures and SVX II chips. Details of the exposure and results are given in DØ Note 3962[12].

Two detectors of each type were tested, with the exception of the outer disks, which were previously studied and are not expected to be damaged significantly. Detectors were irradiated in five steps in the 8 GeV proton beam in the Fermilab Booster. Data were taken at 0, 300, 600, 900, 1500, and 2100 Krad. The devices were irradiated at 5 C and then kept at 5 C for several days (awaiting access to the Booster enclosure) and then annealed at room temperature for two days. After each step the following tests were done:

- Depletion Voltage: A 1063 nm laser test stand was used to determine the voltage needed for full charge collection. The test provides information on charge collection and leakage current as a function of applied voltage. This test is identical to tests performed on production detector assemblies.

- Detector Burn-in: This is a 15 hour test, where the detector is operated at its depletion voltage and stability, noise performance, and leakage currents are measured. This is also a standard production test. Noise thresholds were also studied by performing short burn-ins at various voltages.

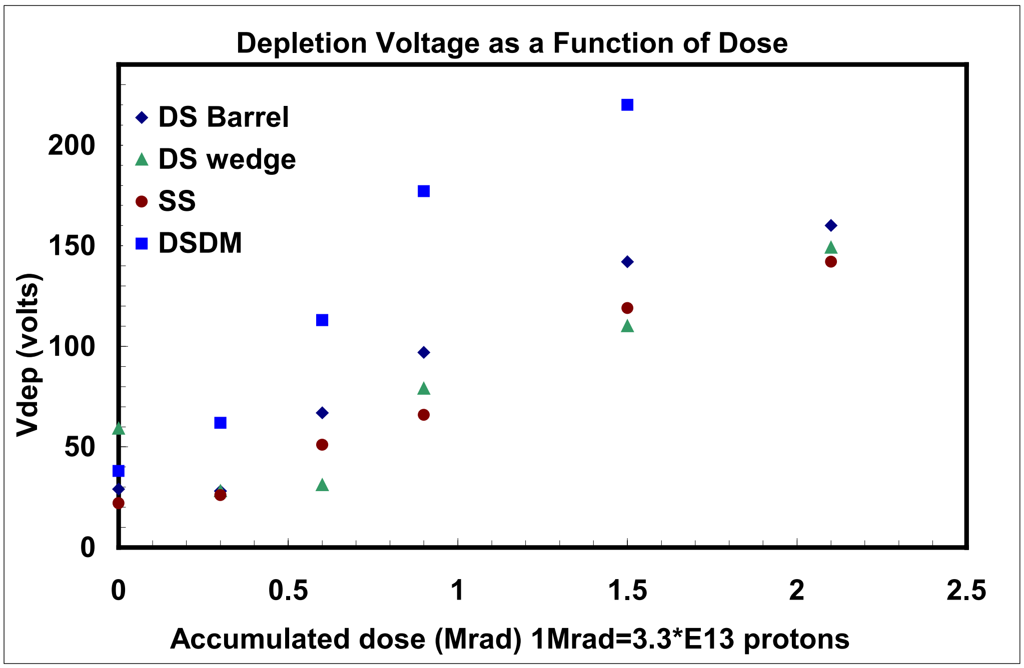

Figure 3 Measured depletion voltage as a function of dose. The depletion voltage of the DSDM detector could not be measured at 2.1 Mrad due to high currents.

Figure 3 shows the measured depletion voltage as a function of dose. Most detector types perform as expected from ROSE collaboration studies. However the DSDM ladders show a rise of depletion voltage that is more than a factor of two faster than other device types. This is particularly serious because these devices are used in the inner layers of barrels 2-5. DSDM devices differ from the others in two ways – they are manufactured using 6" silicon wafer technology and they use a ~1.5 mm thick PECVD (plasma enhanced chemical vapor deposition) layer as insulation between the two metal layers. To understand this effect we performed a separate exposure of test structure diodes from the same 6" wafers that do not have the PECVD layer. These diodes have depletion characteristics similar to the other detector types, indicating that the additional

PECVD layer or the double metal processing causes the increased sensitivity to radiation[13].

For double-sided detectors the limit on detector lifetime is expected to be unacceptably large depletion voltage. We expect to split the bias voltage between the p and n sides to limit the voltage across the AC coupling capacitors, but this ratio is limited by onset of micro-discharge in the ladders. Capacitor breakdown was specified to be greater than 150V and tested by DØ on each detector to 100V [14]. Figure 4 shows the number of shorted capacitors on a typical detector as a function of applied voltage. Breakdown thresholds may be further lowered by aging and mechanical damage incurred during micro-bonding. Capacitor shorts cause SVX chip inputs to saturate, driving current into the chip substrate, and forcing saturation and pedestal shifts in several neighbor channels. Such areas are known as "black holes". This effect limits double-sided detector operation to less than 100-120 V per side.

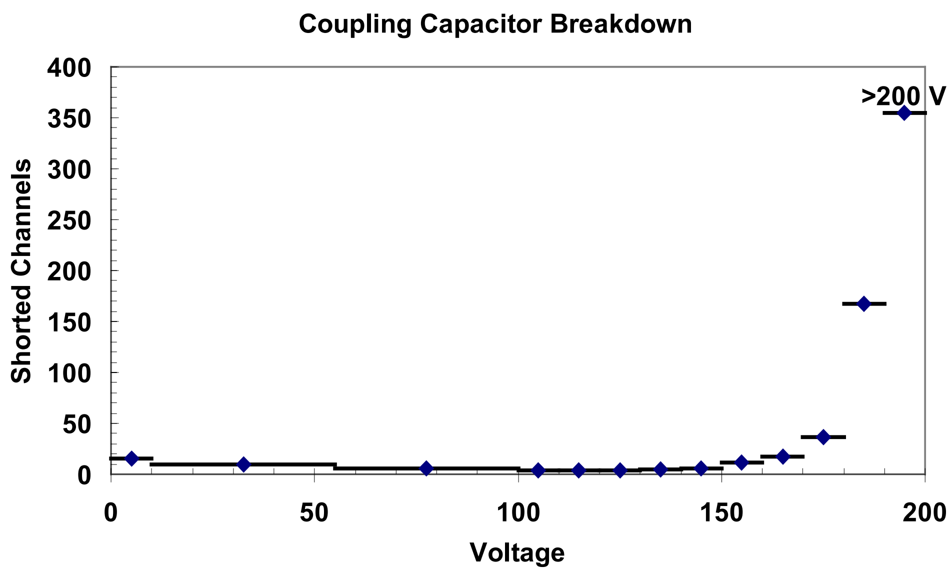

Figure 4 Coupling capacitor breakdown distribution for a typical Micron detector with 648 channels.

The micro-discharge effect is dramatic in many of the devices from Micron; in many detectors the voltage across the coupling capacitor on the n-side has to be limited to a few volts to avoid breakdown[15]. Micro-discharge is caused by an increase in the magnitude of the electric field at the p-n junction caused by fields associated with the AC coupling structure. Excess charge in the oxide or misalignment of the aluminum layer can lower the breakdown threshold. In SMT production testing each double-sided detector had to be tested to determine the maximum tolerable p-side voltage. After irradiation the junction migrates from the p to the n side (type inversion) and the fixed positive oxide charge increases rather than lowers the breakdown threshold. Figure 5 shows noise as a function of dose for double sided detectors tested in the Fermilab Booster. The increase in noise beyond 1.5 MRad for the DSDM detectors shows characteristics typical of micro-discharge, including sensitive dependence on AC coupling voltage and decrease in noise with increasing temperature[16]. Micro-discharge is “flicker noise” and causes large breakdown noise pulses on a fraction of events.

Figure 6 shows the noise for detectors irradiated to 2.1 Mrad as a function of bias voltage. The micro-discharge breakdown causes the rapid rise of noise as a function of bias. This decrease in signal/noise as a function of breakdown threshold increases with increasing temperature as expected due to the decrease in carrier mobility. The rapid increase in noise as a function of bias when micro-discharge threshold is exceeded motivates us to define the lifetime of the detector as the onset voltage of micro-discharge. From our booster data we expect the n-side noise will become unacceptable for bias voltages between 130 and 170 volts for operating temperatures near 0 degrees. The p-side (ϕ-measuring) noise appears to be tolerable to ~200 V. The micro-discharge threshold is sensitive to the relative alignment of the implants and aluminization as well as the amount of trapped oxide charge. In unirradiated detectors micro-discharge breakdown thresholds vary from a few volts to greater than 100 volts for sensors of the same type. There is therefore considerable uncertainty in the breakdown thresholds for the 48 inner layer detectors after irradiation. Our best estimate is that the tracker will lose precision r-z measurements at a total bias of 150 volts and that the inner layer will be unusable at a total bias exceeding 200 volts.

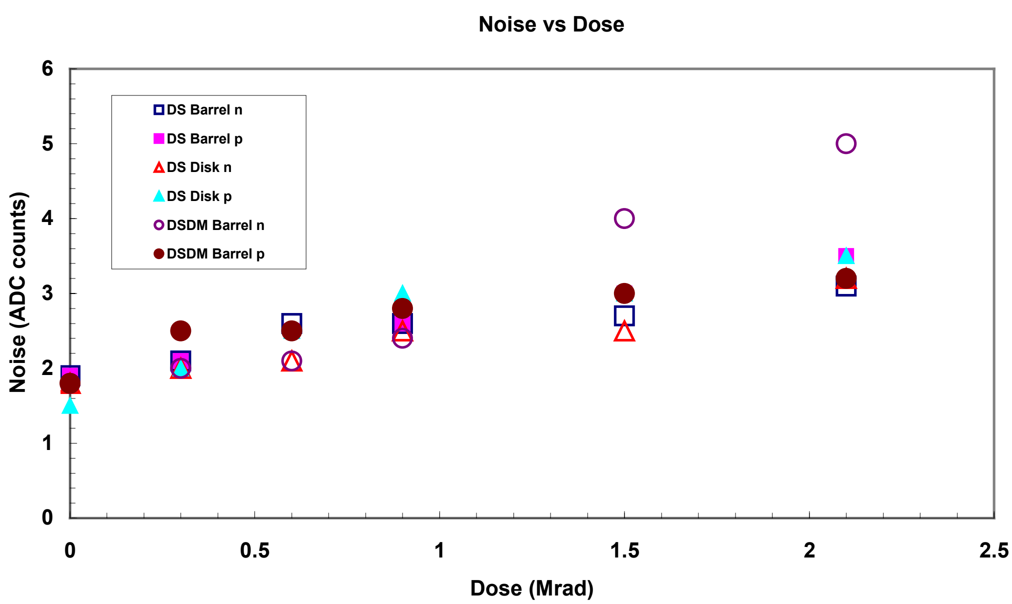

Figure 5 Noise vs dose for double sided detectors at operating voltage. Open symbols are n-side measurements. The DSDM detector could not be fully depleted at 2.1 MRad. One MIP at normal incidence is 26 ADC counts.

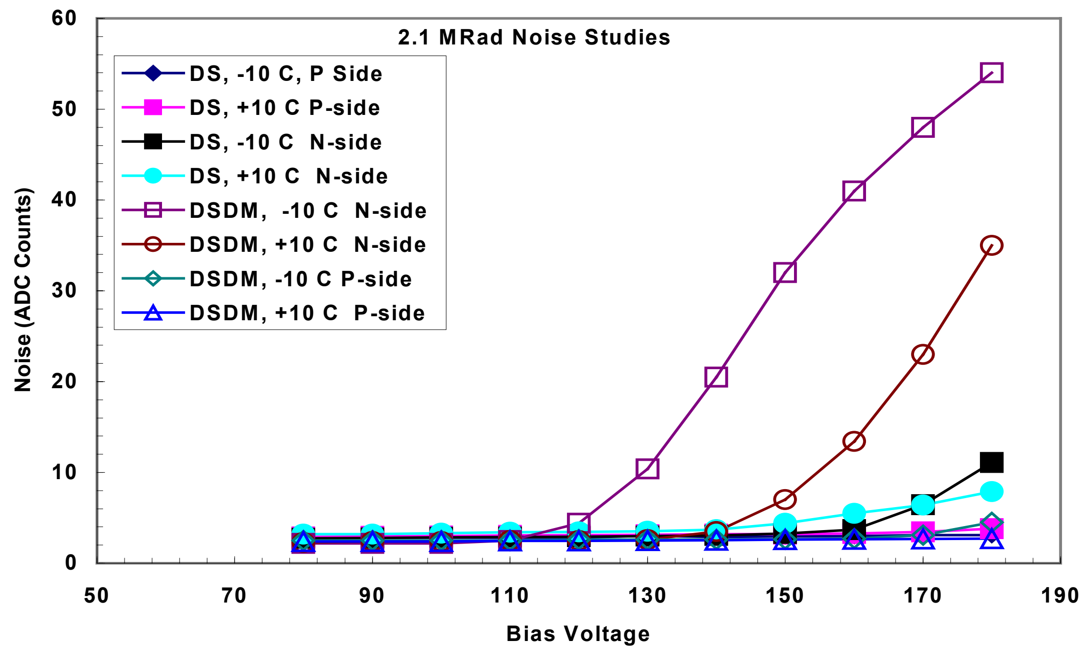

Figure 6 Noise as a function of bias voltage and temperature for detectors irradiated to 2.1 MRad.

IV. Dose Expected in Run II

The dose expected in the DØ silicon detectors in Run II was originally based on GEANT/GCALOR studies[17 18] and updated with CDF SVX Run I studies[19 20 21]. The CDF studies measured the integrated particle flux at the sensors by monitoring their leakage currents, $I_L=I_0 \alpha \phi$. There are considerable uncertainties in applying this calculation directly to Run II due to the 2 Tesla field in DØ (vs. 1.5 Tesla in CDF) and differing shielding and halo conditions expected.

DØ uses several techniques to monitor the exposure of the silicon. The silicon is protected by a beam loss monitor (BLM) system, similar to that employed by CDF, used to abort the beam during periods of high losses. These systems are not sensitive to the smaller, continuous losses during the store. There are a series of TLDs arrayed near the beam pipe. These will be removed and measured in the January 2003 shutdown. DØ has added a set of "finger" diodes at four radii which are capable of monitoring losses continuously during a store. A recent store is shown in Fig. 7. We have used the fingers to establish that >85% of the absorbed dose comes during the store despite occasional large losses during shot setup. We have also used the fingers to confirm that losses due to looping tracks at ~2.7 cm radius are constant between 1.5 and 2 Tesla [22], allowing us to apply the results of previous CDF studies with more confidence.

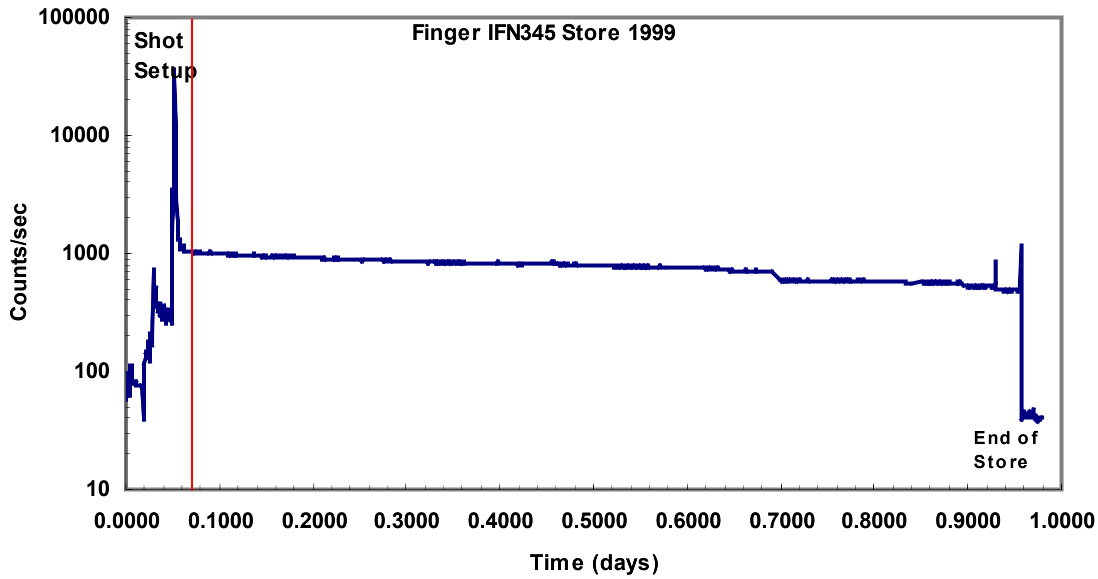

Figure 7 Loss rate recorded by inner SMT finger counter during a recent store.

The most reliable estimate of total absorbed dose is given by the increase in leakage current as a function of luminosity. The leakage current damage is characterized by a damage constant, α, where $\alpha = 2.9 \times 10^{-17}$ A/particle cm^2 after full annealing at 20 deg C. The particle flux, ϕ, is characterized as the equivalent flux of 1 MeV neutrons, which is also used to characterize changes in depletion voltage. Corrections must be made for annealing effects and temperature dependence, $I \sim T^2 e^{(-1.23\text{eV}/kT)}$. These corrections have ~30% uncertainty. Figure 8 shows the current as a function of luminosity for several single sided inner layer ladder gangs during the September-November 2002 running period.

Each bias channel supplies four ladders and must be corrected for sublayer radius, detector area, temperature, and the effective value of α including an estimate of annealing effects. Figure 9 shows our preliminary results for flux as a function of radius. Our measured fluence factor of $3.1 \pm 0.9 \times 10^{12}$ one MeV neutron equivalent cm^{-2}/fb^{-1} at r = 2.7 cm is consistent with the CDF run 1 result of 4.1×10^{12} /cm^2 fb^{-1} at r=2.7 cm. The DØ errors are statistical only. For consistency with previous calculations we will continue to use the CDF Run I value of $\Phi(r) = 2.19 \pm 0.63 \times 10^{13} (r[\text{cm}])^{-1.68}$ cm^{-2}/fb^{-1} for lifetime calculations in section V.

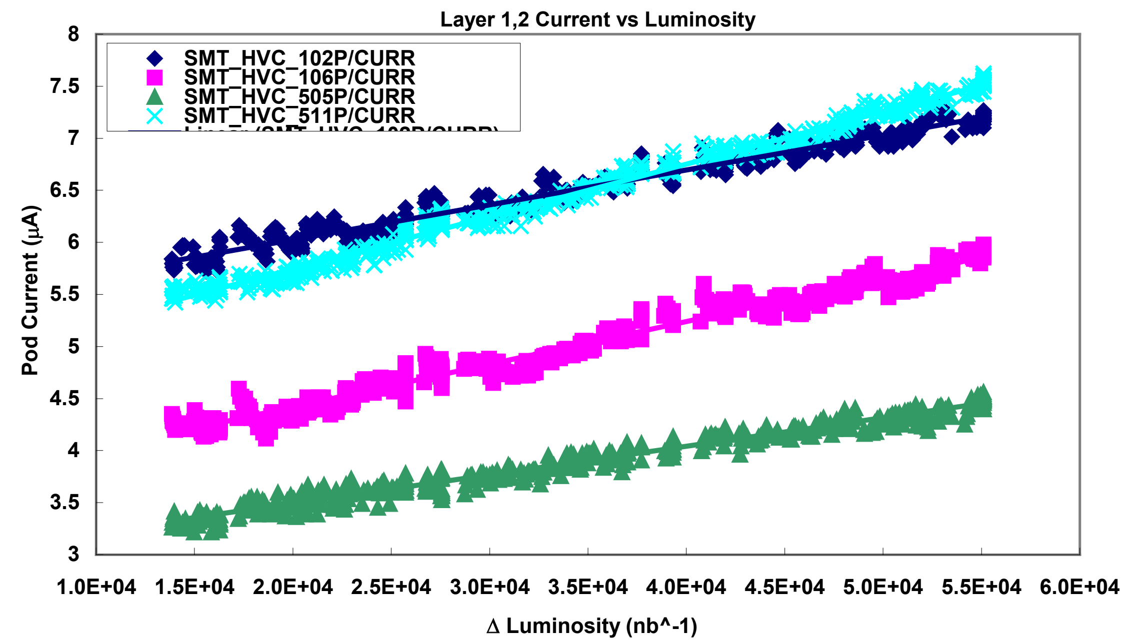

Figure 8 Pod current vs luminosity single sided inner layer detectors

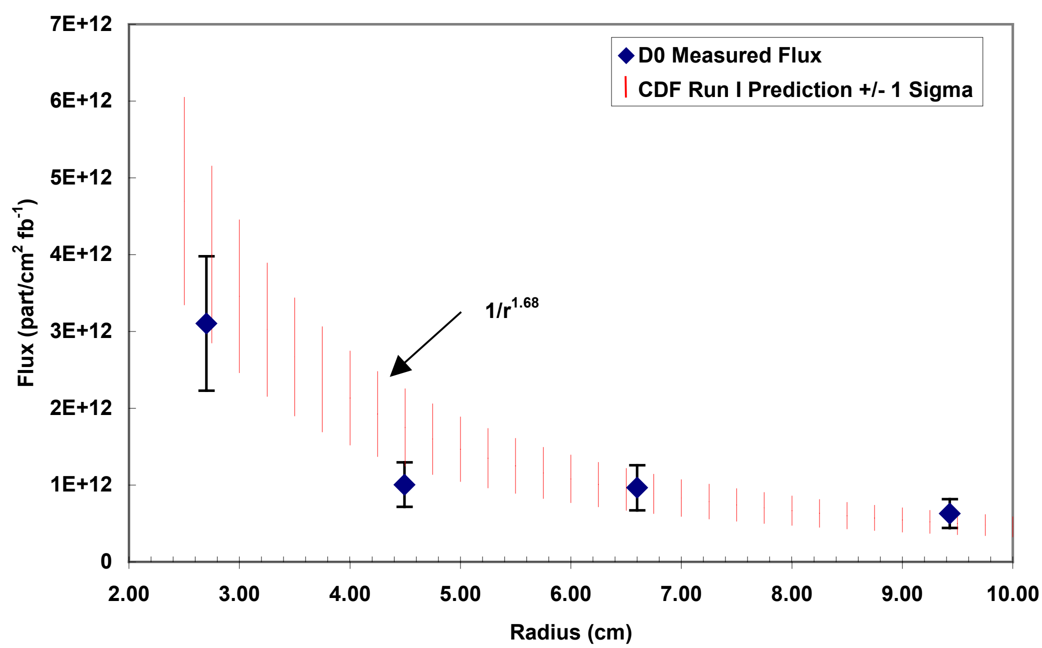

Figure 9 Particle flux as calculated from leakage current increase as a function of radius. Errors on the DØ points are statistical only. The vertical lines are the CDF Run I prediction.

V. SMT Lifetime Expectation

In section III we concluded that the SMT will lose n-side information from the inner layer at ~150 V and the inner layer will become unusable at ~200 V. The inner layer DSDM detector depletion voltage will exceed 150 V at 0.8 MRad and 200 V at 1.1 Mrad. Using a flux factor of 4.1×10^{12} particles/cm^2 fb^{-1} at 2.7 cm as discussed in section IV and 1.8×10^{13} one MeV neutrons/ Mrad, we obtain

Significant loss of channels in layer 1 with integrated luminosity above 3.6fb^{-1}
All channels on layer 1 dead after an integrated luminosity of 4.9 fb^{-1}.

This is our current best estimate given current knowledge of Tevatron losses and sensor radiation damage. The radiation damage will be incremental and there may be particular choices of operating parameters or unexpected long term annealing effects that may influence detector lifetime. The point where the tracker is deemed to be unusable cannot be specified precisely; certainly we can survive a few percent of lost channels, but likely cannot survive 50%. This "best" estimate of the inner layer lifetime has significant uncertainty and the detector inner layer could start to fail before the nominal 3.6 fb^{-1}. Finally, as we noted in Section I, there are strong motivations for silicon replacement simply due to the high occupancies expected in the high luminosity Run IIb environment. Timely replacement of the DØ silicon tracker is essential for success of the Run IIb physics program.

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